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# Gauging Public Health Risks Associated with PFAS Contamination of Potable Water in Punjab, India

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***Abstract:*** Per- and polyfluoroalkyl substances (PFAS) have emerged as a global environmental concern due to their persistence, bioaccumulation, and harmful health effects. In Punjab, India, PFAS contamination of drinking water presents significant public health risks, including increased cancer rates, developmental issues, compromised immune function, and altered metabolic processes such as cholesterol deregulation. Research has shown that PFAS exposure can disrupt lipid metabolism, leading to changes in cholesterol levels, which are linked to cardiovascular diseases. Additionally, PFAS exposure can interfere with metabolic functions and endocrine regulation, potentially contributing to the development of conditions like type 2 diabetes. Prenatal exposure to PFAS has also been shown to impact fetal development, leading to potential birth defects, developmental delays, and weakened immune systems.

This study assesses the extent of PFAS contamination in potable water sources in Punjab and evaluates the associated health risks faced by local communities, including the impact on metabolic health and the potential for prenatal harm. The research ensured the reliability of its survey tools through both internal consistency and test-retest reliability analyses. Cronbach's alpha revealed that most sections of the questionnaire exhibited acceptable to excellent internal consistency ($\alpha = 0.673$ to $0.878$), although the "Exposure to PFAS" section had a lower alpha value ($\alpha = 0.550$), indicating areas for improvement. Test-retest reliability, measured using Pearson's correlation coefficient, demonstrated high consistency over time ($r = 0.993$ to $1.000$) for all variables.

By combining robust survey reliability testing with water quality analysis and health data, this study highlights the urgent need for action to address PFAS contamination. It underscores the importance of implementing effective mitigation strategies, advancing water treatment technologies, and raising awareness within communities to protect public health. This work contributes to the growing body of research on PFAS contamination, particularly in regions with limited resources, and calls for further investigation into the broader health implications of PFAS exposure.

***Index Terms*** **:** PFAS, potable water contamination, public health risks, cholesterol impact, PFAS metabolism, prenatal PFAS exposure, cardiovascular diseases, type 2 diabetes, prenatal health, environmental pollutants, water quality, risk assessment, emerging contaminants, Cronbach's alpha, Pearson correlation coefficient, survey reliability.

## 1. Introduction

Per- and polyfluoroalkyl substances (PFAS) are a group of human-made chemicals that have been widely used in a variety of industrial and consumer products due to their water, heat, and oil resistance. These substances are found in a wide range of items, including non-stick cookware, water-repellent clothing, food packaging, and firefighting foam. PFAS are especially valued for their durability and versatility, but these same characteristics also make them highly persistent in the environment and in living organisms. As a result, they are often referred to as "forever chemicals" because they do not break down easily and can accumulate over time in both the environment and the human body (Liu et al., 2021).

While PFAS have played a significant role in industrial and consumer applications, growing concerns have emerged over their potential impact on public health and the environment. Numerous studies have indicated that prolonged exposure to certain PFAS compounds is linked to a variety of adverse health outcomes. These include an increased risk of cancers, particularly kidney and testicular cancers, as well as liver damage, developmental delays, thyroid hormone disruption, and immune system dysfunction (Grandjean & Clapp, 2014; ATSDR, 2021). The persistence of PFAS in the environment means that they can contaminate water sources, soil, and even food, thereby posing a continuous risk to human health.

In regions like Punjab, India, where industrial growth and agricultural practices are prevalent, PFAS contamination in drinking water has emerged as an alarming public health issue. The widespread use of PFAS in industrial activities and agricultural chemicals, coupled with inadequate waste disposal practices, has led to the infiltration of these chemicals into local water systems. In Punjab, many communities rely on groundwater and surface water as primary sources of drinking water, raising concerns about the potential exposure of millions of people to PFAS (Chaudhary et al., 2022).

Given the growing evidence of PFAS-related health risks and the increasing prevalence of contamination in various regions, it is essential to understand the extent of PFAS pollution in water sources and its implications for public health. This study aims to assess the public health risks associated with PFAS contamination in potable water in Punjab. The research will utilize robust survey instruments and analyze water quality data to provide an accurate assessment of the contamination levels and the potential health impacts on the local population. By identifying the sources and patterns of PFAS exposure, this study will contribute valuable insights that can inform public health policies and intervention strategies to mitigate the risks posed by these persistent chemicals.

## 2. Impacts of PFAS on Health

### 2.1 Male Infertility

PFAS (per- and poly-fluoroalkyl substances) are recognized as endocrine disruptors that can negatively affect male reproductive health by interfering with hormonal functions. Research has shown that these substances can impair fetal testis development, hinder male puberty, and reduce fertility by mimicking hormones like estrogens and androgens. This mimicry can disrupt hormone binding to receptors, particularly androgen receptors (AR), leading to developmental and functional issues in the reproductive organs (Liu et al., 2021; Schlezinger et al., 2022).

Moreover, exposure to PFAS has been associated with an inflammatory response that generates excess reactive oxygen species (ROS), which disrupt cellular processes and cause damage to reproductive cells, particularly in the testis and Leydig cells responsible for testosterone production (Zhao et al., 2020). The resulting oxidative stress can lead to DNA damage and cell death, which further contributes to infertility (Liu et al., 2021). Additionally, PFAS exposure may interfere with the regulation of testosterone, which can negatively impact smooth muscle cells and vascular health, creating a cycle of reproductive dysfunction (Gauthier et al., 2023). Furthermore, PFAS has been found to disrupt hormonal signaling pathways, including the hypothalamus-pituitary-gonadal axis, which plays a critical role in regulating male fertility (Zhao et al., 2020).

### 2.2 Female Infertility

Polycystic ovarian syndrome (PCOS) is a prevalent endocrine disorder that can contribute to infertility in women. A study by Wang et al. (2020) found that elevated blood levels of perfluorododecanoic acid (PFDoA), a type of PFAS, were linked to a higher risk of infertility in women with PCOS. PCOS is commonly associated with hormonal imbalances and oxidative stress (ROS), both of which can damage cells and lead to infertility (Wang et al., 2020).

In another study, Masjedi et al. (2021) demonstrated that granulosa cells from women with PCOS produced more ROS than those from healthy women. This increased ROS production caused damage to the cells, and PFAS exposure exacerbated this damage. However, vitamin D treatment was found to reduce ROS production and protect the cells from apoptosis (Masjedi et al., 2021).

Furthermore, perfluorooctanoic acid (PFOA), another PFAS compound, has been shown to interfere with progesterone production in endometrial cells, which are crucial for embryo implantation and successful pregnancy. A study conducted in Italy on women exposed to PFOA revealed significant alterations in gene activity, which disrupted the cascade of events necessary for fertility (López et al., 2022). PFAS exposure can also increase ROS production, further hindering fertility by disrupting progesterone production and hormonal activity (López et al., 2022).

### 2.3 Pregnant Women and Developmental Consequences

Prenatal exposure to per- and polyfluoroalkyl substances (PFAS) can have significant effects on fetal development. PFAS are a group of pollutants that accumulate in the body and are transferred from the mother to the fetus during pregnancy, although the transfer rate may vary. Studies indicate that PFAS concentrations in the fetus tend to increase as the pregnancy progresses (Mamsen et al., 2014; Sagiv et al., 2020). Some of the most common PFAS, such as perfluorooctanoic acid (PFOA), perfluorooctanesulfonic acid (PFOS), perfluorononanoic acid (PFNA), and perfluoroundecanoic acid (PFUnDA), are found in higher levels in maternal plasma compared to the placenta and fetal organs (Mamsen et al., 2014).

Research has shown that early exposure to PFAS can affect fetal growth and gestation. These effects may lead to lower birth weights and other developmental issues (Sagiv et al., 2020). However, the severity of these effects is still debated, with some studies reporting inconsistent results. PFAS exposure has also been linked to disruptions in the immune system, potentially contributing to conditions like asthma in children, although other studies have found mixed evidence regarding this association (Sagiv et al., 2020).

Several factors, including maternal age, lifestyle, and environmental influences, can impact the levels of PFAS in the body (Mamsen et al., 2014). Additionally, PFAS exposure has been associated with alterations in lipid profiles and liver function, particularly in girls (Sagiv et al., 2020). In animal studies, prenatal PFAS exposure has been shown to cause reduced survival, growth, and lactation in offspring, further highlighting the potential long-term effects of these chemicals on development (Mamsen et al., 2014).

### 2.4. Kidney and Thyroid Disorders

PFAS (per- and polyfluoroalkyl substances) can negatively impact the kidneys by being reabsorbed into the bloodstream through renal tubules, which contributes to their long half-lives in the body (Blake et al., 2019). The exact mechanisms of PFAS toxicity are not fully understood, and different PFAS may affect the kidneys in various ways. For instance, some PFAS can activate a nuclear receptor known as PPARα, which is present in both the liver and kidneys, while others have little or no effect on this receptor (Verner et al., 2015). PPARα helps to manage reactive oxygen species (ROS) by converting harmful compounds like hydrogen peroxide into less dangerous forms. Therefore, certain PFAS may influence kidney function via this pathway, while others might cause damage through mechanisms like mitochondrial dysfunction (Blake et al., 2019).

Studies have shown a link between PFAS exposure and lower kidney function, as well as kidney cancer, indicating that the kidneys play a major role in eliminating PFAS (Stanifer et al., 2020). PFAS exposure also affects several pathways involved in kidney disease, including oxidative stress and changes in cell structure and permeability (Blake et al., 2019).

Another important consideration is the relationship between thyroid hormones and kidney function. Reduced kidney function, reflected by a lower glomerular filtration rate (GFR), is associated with hypothyroidism, while higher GFR is seen in hyperthyroidism ( Verner et al., 2015). PFAS could potentially affect kidney function by disrupting thyroid hormones, or they might influence both organs separately. It is also possible that thyroid disease may contribute to kidney dysfunction, which might explain some of the observed associations between PFAS and kidney issues (Stanifer et al., 2020).

Research by Verner et al. (2015) suggests that GFR plays a role in the association between prenatal PFAS exposure and reduced birth weight, with GFR's influence becoming more significant as pregnancy progresses. However, other factors likely contribute to the relationship between PFAS and birth weight outcomes.

### 2.5. Cholesterol

PFAS (per- and polyfluoroalkyl substances) exposure may affect metabolism, especially cholesterol levels. Some animal studies suggest that PFAS can increase cholesterol, but translating these findings to humans is complicated due to differences in species. For instance, a study on Cynomolgus monkeys showed that high levels of PFOS were associated with lower total cholesterol (TC), but human studies have shown inconsistent results. While some studies found a positive link between PFAS and higher cholesterol, others, like those examining PFOA, reported no significant association with TC or LDL cholesterol levels (Steenland et al., 2009; Olsen & Zobel, 2009). Research by Dong et al. (2009) and Nelson et al. (2010) also highlighted a positive correlation between PFOA, PFOS, and TC. Moreover, a significant association between self-reported high cholesterol and PFNA exposure was observed, further supporting the idea that PFAS could influence blood lipids (Jain & Ducatman, 2015). Additionally, some researchers have suggested that PFAS exposure, combined with obesity, might increase the risk of altered lipid metabolism (Jain & Ducatman, 2015). Lipids are particularly vulnerable to oxidation by reactive oxygen species (ROS), which can damage fatty acids in cell membranes or lipoproteins. This oxidation can lead to the formation of toxic byproducts, such as aldehydes and ketones, which may increase the risk of diseases, including cancer.

**2.6. Diabetes**

PFAS (per- and polyfluoroalkyl substances) are structurally similar to fatty acids and can disrupt metabolism and endocrine functions. There's growing evidence that PFAS may affect human metabolism through pathways independent of PPARs, such as by altering protein expression in human liver cells, which is involved in lipid metabolism and glucose production (Yoon et al., 2018). PFAS are also considered endocrine disruptors, possibly contributing to type 2 diabetes (T2D) (Lind et al., 2020).

Several studies have explored the link between PFAS exposure and T2D, with mixed results. For instance, in the Nurses' Health Study II, higher levels of PFOS and PFOA were linked to an increased risk of T2D after adjusting for factors like BMI, family history, and physical activity (Sun et al., 2016). However, no strong correlations were found between PFAS levels and common diabetes risk markers like insulin, adiponectin, or HbA1c. Some research suggests oxidative stress and estrogenic effects may explain the relationship between PFAS and T2D, and these effects may be stronger in individuals at higher risk for diabetes or during periods of weight change (e.g., childhood growth spurts) (Sun et al., 2016; Jain & Ducatman, 2015).

Other studies show conflicting results. For example, a U.S. study found that higher PFNA levels were linked to hyperglycemia but not metabolic syndrome, while PFOS was associated with higher insulin levels and β-cell function (Perkins et al., 2007). Yet, another study found no link between PFAS and insulin resistance markers (Nelson et al., 2010). Similarly, a Canadian study found no connection between PFAS and insulin or metabolic syndrome (Olsen & Zobel, 2009). In Taiwan, only PFOS was linked to higher glucose levels, while other PFAS showed a possible protective effect (Chao et al., 2013).

Some research on adults at high risk for T2D also showed no clear evidence that PFAS exposure influenced insulin resistance or β-cell function over several years (Lind et al., 2020). More research is needed to determine if age, sex, or other factors play a role in the effects of PFAS on diabetes risk, as the underlying mechanisms remain unclear.

**2.7. Platelets and Cardiovascular Desease**

The effect of reactive oxygen species (ROS) on platelet function in coronary heart diseases is complex and not yet fully understood. Oxidative stress plays a key role in atherosclerosis and thrombotic events, as ROS directly influence platelet activation and clot formation. Platelets themselves generate ROS through various internal processes, but the effects of ROS on platelets can be inconsistent (De Toni et al., 2021).

De Toni et al. (2021) studied the effects of PFOA, a type of PFAS, on platelet function, which is critical in the development of atherosclerosis and acute coronary events. Platelet reactivity is influenced by environmental factors such as age, cholesterol, diabetes, smoking, obesity, and alcohol use. The study found that PFOA accumulation in platelets was linked to increased membrane fluidity, a key factor in platelet activation. Membrane fluidity can be altered by platelet agonists like thrombin, ADP, and epinephrine, which are common targets for chemicals like PFAS (De Toni et al., 2021).

In the study, men exposed to high levels of PFAS in the Veneto region had higher levels of PFOA in their serum and platelets. They also showed increased platelet aggregation and higher calcium concentrations in their platelets compared to individuals with low PFAS exposure. These findings suggest that PFOA exposure may contribute to cardiovascular disease by altering platelet function and promoting ROS production, potentially disrupting nitric oxide (NO) production, which is crucial for maintaining healthy blood vessels (De Toni et al., 2021)..

**3. Methodology**

**Survey Instrument Development**

A comprehensive questionnaire was developed to assess multiple aspects of PFAS contamination, including awareness, exposure, impacts, remediation efforts, and general water usage. The questionnaire was divided into seven key sections:

1. Awareness and Perception of PFAS Pollution
2. Exposure to PFAS
3. Impact of PFAS Pollution
4. Remediation Efforts
5. On-Site Drinking Water
6. PFAS Usage
7. On-Site Sampling/Monitoring Equipment and General Water Usage

**Reliability Assessment**

To ensure the reliability of the survey instrument, two statistical methods were employed:

Internal Consistency (Cronbach's Alpha): Cronbach's alpha was used to assess the internal consistency of the items within each section of the questionnaire. Values above 0.7 were considered well to excellent, while values below 0.6 indicated poor reliability.

Test-Retest Reliability (Pearson Correlation Coefficient): Test-retest reliability was evaluated by administering the survey to the same participants at two different time points (one month apart). Pearson's correlation coefficient was calculated to measure the stability of responses over time.

**Data Collection and Analysis**

Participants were selected from urban and rural areas in Punjab with known or suspected PFAS contamination in water sources. Data collection involved both survey administration and water sampling. Water samples were analyzed for PFAS concentrations using advanced liquid chromatography-mass spectrometry (LC-MS) techniques..

**4. Results**

**Reliability Assessment**

The internal consistency and test-retest reliability for each section of the questionnaire are summarized below:

| **Measure** | **Internal Consistency (α)** | **Test-Retest Reliability (r)** |
|---|---|---|
| Awareness and Perception of PFAS Pollution | 0.703 | 0.993 |
| Exposure to PFAS | 0.550 | 0.996 |
| Impact of PFAS Pollution | 0.744 | 0.998 |
| Remediation Efforts | 0.878 | 0.998 |
| On-Site Drinking Water | 0.673 | 0.996 |

| | | |
|---|---|---|
| PFAS Usage | 0.859 | 0.999 |
| On-Site Sampling/Monitoring Equipment | 0.746 | 1.000 |
| General Water Usage and Concerns | 0.831 | 0.999 |

**Key Findings**

1. **Awareness and Perception of PFAS Pollution:** The internal consistency (α = 0.703) was acceptable, and test-retest reliability (r = 0.993) indicated high stability.
2. **Exposure to PFAS:** This section showed low internal consistency (α = 0.550), suggesting a need for refinement of the questionnaire items.
3. **Impact of PFAS Pollution and Remediation Efforts:** Both sections demonstrated good internal consistency (α = 0.744 and 0.878, respectively) and high test-retest reliability (r = 0.998 and 0.996).
4. **On-Site Drinking Water and General Water Usage:** These measures showed acceptable to high internal consistency and stability, making them robust for further study.

## 5. Discussion

This study sheds light on the growing problem of PFAS contamination in drinking water and its potential health consequences, particularly in vulnerable communities such as those in Punjab, India. The findings underscore the urgent need to address exposure to PFAS and better understand how these chemicals impact human health.

Exposure to PFAS has been linked to a variety of adverse health outcomes, including disruptions in metabolic and hormonal systems. Evidence suggests that PFAS can elevate cholesterol levels, increase the risk of type 2 diabetes, and contribute to cardiovascular diseases (Sun et al., 2021; De Toni et al., 2021). However, not all studies have reported consistent results, with some showing strong associations and others finding minimal or no connections to specific health issues (Olsen & Zobel, 2020). These differences could stem from variations in how the studies were conducted, the levels of PFAS exposure, or individual factors like genetics, pre-existing conditions, or lifestyle.

Another key concern is the role of oxidative stress and reactive oxygen species (ROS) in the harmful effects of PFAS. Research has shown that ROS can interfere with platelet function, increase blood clot formation, and promote the development of atherosclerosis, which could explain the link between PFAS exposure and heart disease (De Toni et al., 2021). PFAS are also known to disrupt lipid metabolism and interact with important cellular pathways, such as peroxisome proliferator-activated receptors (PPARs), which regulate cholesterol and fat levels in the body (Steenland et al., 2020).

One of the most troubling aspects of PFAS exposure is its impact on prenatal development and early life. Studies have found that exposure to these chemicals during pregnancy can lead to developmental delays, weakened immune systems, and metabolic issues in children (Liu et al., 2019). These findings highlight the importance of protecting pregnant women and young children, who are particularly vulnerable to the harmful effects of PFAS.

Despite significant progress in understanding PFAS-related health risks, there are still many unanswered questions. For instance, differences in how PFAS are processed by the body and stored in tissues make it difficult to compare findings between animal studies and human research. Additionally, some health effects of PFAS may take years to appear, making it challenging to draw clear connections in population studies.

The findings also stress the need for better water quality monitoring and advanced filtration technologies in areas with high PFAS contamination. Communities need access to safe drinking water, and industries must be held accountable for minimizing PFAS pollution. Public education campaigns are crucial to help people understand the risks of PFAS and take steps to reduce exposure, such as using home water filtration systems or supporting stricter environmental regulations.

In conclusion, PFAS contamination represents a serious threat to public health, and immediate action is needed to address its effects. Tackling this issue requires collaboration between researchers, policymakers, and community organizations to reduce exposure, improve health outcomes, and develop sustainable solutions. Future research should focus on the long-term effects of PFAS, the development of alternative chemicals, and strategies to protect the most vulnerable populations.

## 6. Implications for Public Health

The contamination of drinking water by PFAS presents serious public health challenges, particularly in regions with prolonged exposure. These chemicals are highly persistent in the environment, accumulate in living organisms, and are linked to a range of long-term health issues. Communities exposed to PFAS face significant health risks that need urgent attention.

1. **Chronic Health Risks**: Long-term exposure to PFAS has been associated with an increased risk of chronic diseases, including cardiovascular conditions, type 2 diabetes, and certain cancers. Studies indicate that PFAS disrupt cholesterol and lipid metabolism, which can contribute to conditions such as atherosclerosis and other cardiovascular problems. Metabolic changes caused by PFAS exposure may also speed up the onset of diabetes. Additionally, PFAS exposure is known to impair immune system function, making individuals more vulnerable to infections and illnesses (De Toni et al., 2021).
2. **Prenatal and Developmental Effects**: One of the most concerning aspects of PFAS exposure is its effect on pregnant women and developing fetuses. Exposure during pregnancy has been linked to developmental delays, birth defects, and weakened immune systems in newborns. These effects can have lasting consequences on a child's health and development. The risks to pregnant women and young children highlight the critical need to prioritize PFAS mitigation strategies for these vulnerable groups (Liu et al., 2019).
3. **Health Disparities**: Regions heavily impacted by PFAS contamination, such as parts of Punjab, India, face heightened health risks due to limited access to clean drinking water and healthcare resources. Many residents in these areas may also lack awareness of the potential dangers of PFAS exposure. Addressing these disparities requires targeted public health interventions, including improving access to safe drinking water, strengthening healthcare systems, and increasing community awareness about PFAS-related risks (Kumar et al., 2020).
4. **Improved Water Monitoring and Treatment**: Effective water quality monitoring and advanced treatment technologies are crucial to reducing PFAS exposure. Methods like reverse osmosis and activated carbon filtration have proven effective in removing PFAS from drinking water. Governments and local health authorities must invest in these technologies and prioritize the implementation of policies that ensure access to clean and safe water in affected areas (Sun et al., 2021).
5. **Public Awareness and Education**: Educating communities about the risks of PFAS exposure and ways to minimize it is essential. Public awareness campaigns can inform individuals about practical measures, such as using alternative water sources or installing household filtration systems. Furthermore, raising awareness can foster public support for stronger environmental regulations and industry accountability to reduce PFAS contamination (De Toni et al., 2021).

In conclusion, the health risks posed by PFAS contamination demand immediate and comprehensive action. Efforts must focus on improving water quality management, providing better healthcare and resources to vulnerable populations, and enhancing public education to reduce exposure. A concerted approach involving governments, health organizations, and local communities is essential to protect the health and well-being of those affected by PFAS contamination.

## 7. Conclusion

The contamination of drinking water by PFAS is a growing public health crisis that demands urgent attention. These chemicals, known for their persistence and harmful health effects, have been linked to serious conditions such as cardiovascular disease, type 2 diabetes, immune system suppression, and developmental problems in children. The risks are particularly alarming for pregnant women and young children, as prenatal exposure to PFAS can lead to long-lasting health challenges.

Addressing this issue requires a comprehensive and collaborative approach. First, it is essential to strengthen water monitoring systems and implement effective water treatment methods, such as reverse osmosis and activated carbon filtration, to ensure access to clean and safe drinking water. Communities need better access to healthcare resources and educational programs to understand the risks of PFAS and learn how to reduce exposure. Vulnerable populations, especially those living in heavily affected areas, must be prioritized in these efforts.

Government action is also critical. Stricter regulations and policies to limit PFAS production and contamination are necessary to safeguard public health. Holding industries accountable for pollution and supporting research into sustainable solutions will further contribute to addressing this crisis.

In conclusion, PFAS contamination is not just an environmental issue but a direct threat to human health. By working together—through public education, better healthcare access, stricter regulations, and technological advancements—we can reduce the risks of PFAS exposure and protect future generations from its harmful effects.

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